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THE CHALLENGE OF UNSTEADY SEPARATING FLOWS

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INTRODUCTION

Unsteady separation occurs in a wide range of fluid flows of practical importance. In many applications, the ideal flow environment of a mechanical device is nominally steady, but the onset of separation is very often accompanied by some degree of undesirable and irregular unsteadiness. Adverse unsteady effects can also arise either due to self-induced motions of a body in a moving stream, or due to fluctuations or nonuniformities in the surrounding fluid. On the other hand, some devices may be required to execute time-dependent motion in order to perform their basic functions. In general, the combination of *unsteadiness* and *flow separation* produces fluctuating forces, vibrations, aero-elastic instabilities, or combinations of these, that are both undesirable and extremely difficult to predict.

The fluctuating fluid dynamic forces associated with unsteady separation can be almost completely stochastic in some cases, such as buffet on an aircraft wing, or highly organized in others, such as the well-known periodic vortex shedding from a wire or cable. Often, however, significant amounts of both random and periodic fluctuations are present, especially in flows at high Reynolds numbers. These flows represent considerable challenges to the research scientist and to the design engineer alike.

The general fluid dynamic problem of unsteady separation at most practical Reynolds numbers remains an unsolved one, and no completely reliable prediction techniques exist at the present time. Instead, the modern design engineer must draw from a combination of approximate theories, empirical correlations of data, and finite difference programs based on uncertain physical modeling of turbulence.

This paper attempts to describe the basic features of several representative classes of problems for which unsteady effects produce strong or unusual changes in the separation characteristics of the flow. Most of the analysis concerns external flow, and the emphasis here is on the physical phenomena involved.

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Numerous comprehensive reviews, e.g., Refs. 1, 2, 9, 12–16, 18, 19, 21, 23, 24, 26–28, and 30, have surveyed the recent literature on various aspects of unsteady fluid dynamics, and no attempt will be made here to cite the long lists of references available in these reviews.

GENERAL CONSIDERATIONS

What are some of the factors that generally distinguish quasisteady and unsteady separated flow behavior in practical situations? From dimensional analysis, large-scale unsteady effects would be expected to become important, (e.g., with regard to overall performance) when some time scale of the physical motion is comparable to the basic fluid dynamic time scale i.e., when $\omega L / U$ or L / Ut are of the order of 1 or greater. Here, the quantities ω, L, and U = the characteristic frequency, length, and velocity, respectively, of the motion; and t = time. For slender-body oscillations, the quantity $k = \omega L / U_x$ is called the reduced frequency, and the relevant characteristic length is normally a streamwise dimension. On the other hand, the characteristic frequency associated with vortex shedding from arbitrary bodies has traditionaly been called the Strouhal number, $S = fL / U$, in which $f = \omega / 2\pi$ = the cycle frequency; L = usually a dimension perpendicular to the flow; and generally, $U = U_x$ if there is a mean flow. Values of S are typically less than but of order unity.

Even at reduced frequencies much less than one, fluctuating fluid dynamic forces may develop which are out of phase with the body motion. This can lead to flow-induced instabilities, such as flutter, that are important to aeroelasticians and structural engineers. This condition of "negative aerodynamic damping," whereby the body extracts energy from the flow during its periodic motion, can also occur in flows that are essentially inviscid, but the phenomenon is often enhanced considerably by separation. Furthermore, certain types of flutter only occur when separation is present.

There are also instances of uniform body motion in which separated viscous shear layers develop hydrodynamic instabilities with distinct periodicity in the near wake. These, in turn, may induce large-scale unsteady fluctuations in the entire flow field. The most familiar example of this phenomenon is vortex shedding from bluff bodies at low Reynolds numbers, but other examples may be cited, as well. Such self-induced, nonlinear, viscous-inviscid interactions usually produce fluctuating pressures and fluid dynamic forces that have no counterpart in purely steady flows.

Another distinction is the rather subtle but fundamental difference in the application of boundary-layer theory to quasisteady and unsteady flow problems. The classical steady boundary-layer equations are incomplete approximations to the Navier-Stokes equations, but at high Reynolds numbers they provide considerable insight and practical information to design engineers. In particular, good estimates of separation and the onset of stall in real flows are often obtained from boundary-layer calculations of the point where the surface shear stress vanishes, i.e., where $\tau_w = \mu (\partial u / \partial y)_w = 0$. This point delineates the onset of reversed flow near the wall. It also happens to be a singular point for the steady two-dimensional boundary layer equations, although not for the Navier-Stokes equations. Even though classical boundary layer theory breaks down here, this mathematically-singular behavior is a useful engineering tool, since

it often correlates well with the onset of significant changes in the entire flow field.

However, the flow-reversal point, where $\tau_w = 0$, has no such special significance in unsteady flow, nor is it a singular point, in general. Within the past 5 yr, a number of flow fields have been analyzed and calculated using boundary-layer techniques downsteam of the unsteady flow-reversal point. The qualitative features of these results are indicated schematically in Fig. 1, which comes from Ref. 22. Under the influence of adverse pressure gradients, the flow in a thin layer next to the surface reverses direction at some station. However, the viscous flow field remains thin and regular in its behavior to some point downstream, where the general features of classical steady separation seem to develop. Since the initial point of low reversal does not exhibit singular
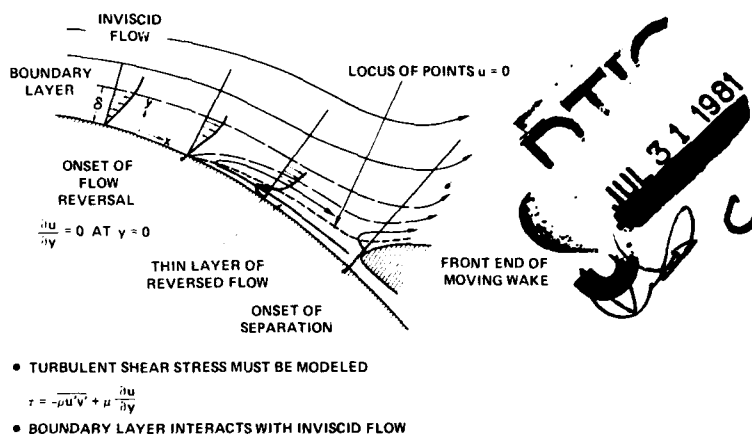

FIG. 1.—Model of Sears and Telionis (22) for Upstream-Moving Separation of Unsteady Boundary Layer

behavior when analyzed within the framework of the classical boundary-layer approximations, the following major questions arise:

1. Does a singularity exist somewhere *else* in the flow, and if so, where?
2. Does this elusive singularity have practical significance analogous to that of the well-known separation singularity in steady flows?
3. To what extent can meaningful and valid estimates of separation-like behavior of real flows be made in unsteady flows, using the classical boundary layer approach?

This whole subject is one of active current research, with a great deal remaining to be learned about the physical significance of unsteady boundary-layer calculations.

EXTERNAL FLOWS PAST BLUFF BODIES

The characteristic unsteady feature of nominally uniform flow past a bluff

body is the strong tendency for the free shear layers to develop into alternate vortices in the wake, over a wide range of flow conditions. The rigid circular cylinder provides the most familiar example of periodic vortex shedding and the associated fluctuating forces that are induced on the body by the vortices in the wake. The following remarks highlight the principal features of this classical problem.

Fig. 2 shows one ideal and two real flow patterns for the circular cylinder. Although the geometry is appealingly simple, there is no discrete point, such as a corner, from which the flow naturally tends to separate. Consequently, the separation phenomenon and the free shear-layer development in the wake are sensitive to the Reynolds number, and unlike thin airfoils, there is no regime that can be described by a potential-flow theory. Parameters R and S are defined in Fig. 3; C_D = the time-averaged drag coefficient; and C_L = the fluctuating lift or side-force coefficient. Only at R $\leqslant$ 1 does the flow even approximately
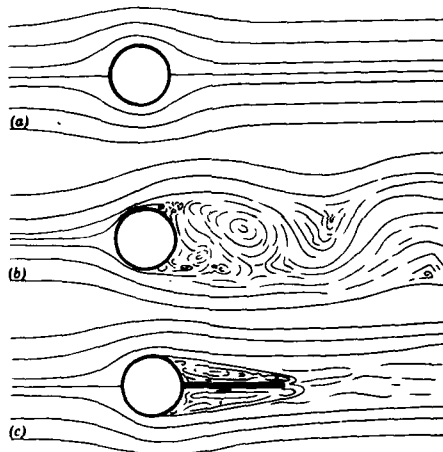

FIG. 2.—Flow Past Circular Cylinder: (a) Potential Flow $C_D = C_L = 0$; (b) R $\simeq$ 10^4 $C_D \simeq 1.1$, $C_L \simeq 0.4e^{i\omega t}$; (c) Splitter Plate $C_D \simeq 0.6$, $C_L \simeq 0$

resemble the sketch in Fig. 2(a) and both unsteady effects and viscous separation are interactively important for R $\geqslant$ 50. On the other hand, the splitter plate shown in Fig. 2(c) destroys the organized vortex shedding by effectively uncoupling the periodic separation from the two sides of the cylinder.

For a basic cylinder without a splitter plate, Fig. 3 indicates the wide ranges of time-averaged drag, fluctuating lift, and Strouhal numbers that can occur at Mach numbers below the onset of shock waves. Unsteady effects are almost always important for R $\geqslant$ 50, although the alternate vortex shedding with dominant periodicity is most pronounced for 100 $\leqslant$ R $\leqslant$ 200,000. This encompasses the vortex-street and subcritical regimes, where the flow near the surface of the cylinder is laminar up to and past the point of separation; transition to turbulence occurs in the wake, if at all. The mean drag coefficient and Strouhal number are well-defined, although considerable scatter occurs in the fluctuating lift or

side-force data, as shown in Fig. 3. Not shown is the unsteady drag, which fluctuates with an amplitude of the order of 0.05–0.10 and a frequency twice that of the lift fluctuations. This occurs because the drag fluctuates with the shedding of each *individual* vortex, whereas the lift fluctuations are synchronized with each *pair* of shed vortices.

Major changes occur at a critical Reynolds number that is of the order of 2×10^5, where transition occurs so quickly in the laminar free shear layer that reattachment of the turbulent flow occurs on the surface of the cylinder.
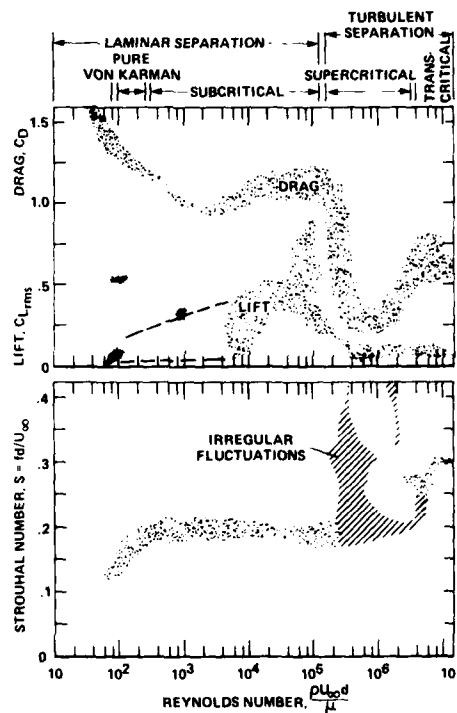

FIG. 3.—Mean Drag, Fluctuating Lift, and Strouhal Shedding Frequency for Rigid Circular Cylinders at Low Mach Number

A short distance farther around the perimeter, the boundary layer reseparates as a turbulent free shear layer. The flow on the rear half of the cylinder changes dramatically as a result of this longer run of thin boundary-layer flow, and the redistribution of pressure causes the well-known large decrease in the mean drag coefficient shown in Fig. 3. The dominant periodicity ceases, and the Strouhal number is usually ill-defined, although significant fluctuations continue. These fluctuations are wide-band, but not completely random. Therefore, a wide range of Strouhal numbers has been reported for this regime; this is indicated by the cross-hatched regions in Fig. 3. The flow in this low supercritical regime

is highly sensitive to free-stream turbulence, surface roughness, and three-dimensional disturbances. Both the mean and the fluctuating forces diminish considerably, but the details of the flow are not well understood nor adequately documented in this regime.

At Reynolds numbers of about 3×10^6 and above for smooth cylinders, transition to turbulence occurs ahead of, and thereby supersedes, the laminar separation bubble. When this occurs, pronounced periodicity in the fluctuating lift reappears, implying a return to some form of periodic vortex shedding. This regime is usually called "transcritical," although the supercritical and transcritical labels are sometimes interchanged in the literature.

Although it has not been established whether there is a Reynolds number above which S, C_D, and C_L remain constant, a predominant Strouhal number becomes rather well-defined at $S \simeq 0.3$ for $R \geqslant 10^7$, and C_D increases approximately twofold above its minimum value at $R \simeq 6 \times 10^5$. The fluctuating lift coefficient is much lower than in the subcritical regime. However, this high Reynolds number regime is only attained at relatively high values of free-stream dynamic pressure, $1/2 \, \rho \, U^2$, or for large diameters. Therefore, the actual side forces are sometimes large enough to induce severe structural vibrations.

UNSTEADY SEPARATION ON STREAMLINED BODIES

Most atmospheric and marine vehicles are designed to avoid separation as much as possible under normal operating conditions. At low Reynolds numbers, organized vortex shedding may occur, analogous to that on bluff cylinders with laminar separation. However, many streamlined configurations operate at high Reynolds numbers, $10^6 \leqslant R \leqslant 10^8$, so that turbulent boundary layers prevail. On high-speed flight vehicles, shock waves may develop which are likely to cause the turbulent boundary layer to separate, whereas stall may occur at lower speeds and high angles of incidence. Furthermore, modern fighter aircraft and missiles often maneuver at such extreme angles of attack that separated vortex flows develop over the fuselage and leading edges of the wings or control surfaces. In any case, turbulence in free shear layers and wakes tends to disorganize the flow, to produce fluctuating fluid dynamic forces, and to compound the analytical difficulties.

For slender bodies at high Reynolds numbers, the unsteady separated flow problems can be roughly classified into three main categories that are very much associated with motion of the body. The term "buffeting" is used to describe the structural response of vehicle components to the aerodynamic excitation produced by flow separation. In this case, the overall body motion is approximately uniform, and the structure flexes slightly and irregularly under the influence of the separation-induced fluctuating airloads. "Stall flutter" refers to oscillations of an elastic body that are caused by separated flow that would be nominally steady in the absence of the body, but which is made unsteady by the flow-induced body motion. Finally, the term "dynamic stall" is often used to describe the unsteady separation and stall phenomena on bodies that are forced to execute time-dependent motion, oscillatory or otherwise, or in cases where gusts or other flow-field disturbances induce transitory stall. Stall flutter and dynamic stall share many common features; the primary *fluid dynamic*

difference is that the amplitude of the motion is normally smaller in most cases of stall flutter.

Buffet.—The turbulent eddies in a separated free shear layer produce velocity and pressure fluctuations that encompass a wide range of frequencies, and the distribution of turbulent energy across the frequency spectrum is normally broadband. Although the amplitudes of these pressure fluctuations are generally much smaller than typical mean values, they are typically 10 times–100 times larger than those of attached boundary layers, as indicated in Fig. 4. Consequently, the separated pressure fluctuations may become greater than the threshold levels that are required to excite the normal modes of vibration of a structure. This resonant fluid dynamic excitation of structural vibrations is characterized by the level, scale, and degree of correlation of the pressure fluctuations.

The earliest investigations of aircraft buffeting dealt with often catastrophic vibrations of tails operating in the separated wake of the main wing, or of
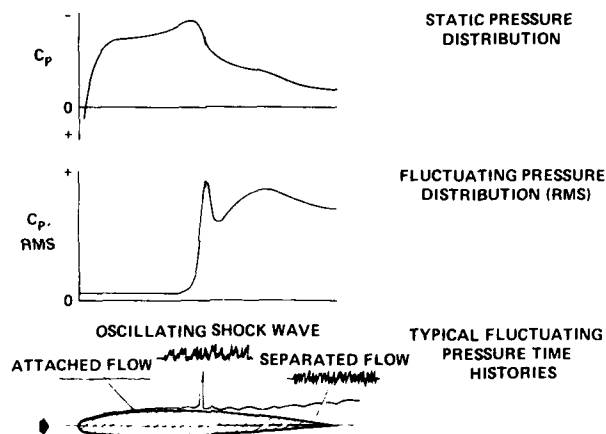

FIG. 4.—Buffet on Airfoil in Transonic Flow

the wing-fuselage junction (9). An analogous bluff-body problem would be the vibrations induced by the impact of the external wake of one tube on another in a multiple-tube, crossflow-type heat exchanger. Buffet may also occur on the wing itself, of course, and this is the more common aeronautical problem today. Wing buffeting of modern aircraft and missiles generally occurs at the extremes of the operational flight envelope, either near $C_{L,max}$ during landing or maneuvers, or near the onset of transonic drag divergence in cruise. Maneuver limitations and drag divergence invariable involve separation induced by shock waves.

Although the onset of flow separation and buffet can be estimated by a combination of boundary-layer methods and potential flow theory, no reliable theoretical or numerical technique exists for predicting the randomly fluctuating pressures in turbulent separated shear flows. Consequently, the design engineer must rely on correlations of experimental data and model tests in wind tunnels for estimates of aerodynamic characteristics, structural vibrations, and fatigue

loads. The fluid dynamic characteristics are often inferred or measured directly on conventional rigid models or surfaces. However, it has not been established to what extent the statistical characteristics of the aerodynamic exciting forces are essentially independent of the motion of the body surface. Further progress in the prediction of buffet awaits advances in the fundamental understanding and calculation of separation induced by shock waves.

Unsteady Shock-Wave Boundary-Layer Interaction.—Shock waves that terminate in the vicinity of boundary layers are seldom steady. This is particularly true of normal shock waves which occur on transonic wings and control surfaces, as examined previously in connection with Fig. 4. Three of the more common types of shock-wave boundary-layer interactions are depicted in Fig. 5. In some cases, the interactions are observed to oscillate periodically with relatively large amplitudes; these fluctuations can cause severe buffeting, flutter, or control-surface buzz.
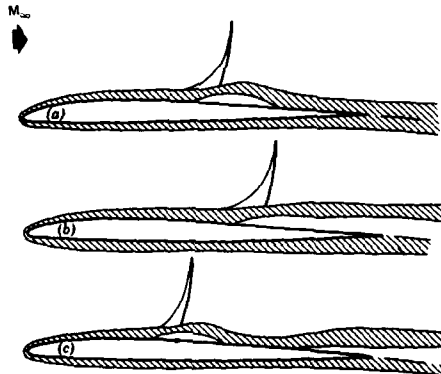

FIG. 5.—Shock-Wave Boundary-Layer Interaction on Airfoils in Transonic Flow: (a) Shock-Induced Turbulent Separation Bubble; (b) Shock-Induced Turbulent Separation; (c) Shock-Induced Separation Bubble and Trailing Edge Separation

Even in the absence of boundary-layer separation, mixed subsonic and supersonic flow fields become rather complicated when unsteadiness is introduced. These complications are often explained using the example of an airfoil with an oscillating flap; see Fig. 6. The sketch shows the propagation of expansion and compression waves as the flap deflection increases, starting from a small downward deflection and a fully developed flow field. The downward flap deflection causes the local flow to accelerate to a higher local Mach number, M, on the upper surface and to decelerate on the lower surface. It is important to note that signals from the oscillating flap only reach the leading edge via the so-called receding waves, which propagate forward at the local sonic speed minus the local flow velocity, and which must detour around the shock wave. Thus, a finite time lag occurs between the motion of the flap and the readjustment of the flow over the leading edge.

The effects of oscillatory flap motion on the flow-field development, especially the shock wave motion and strength, depend in a rather complicated manner

upon the free-stream Mach number and upon the amplitude and frequency of the flap deflection. As the flap moves downward, e.g., the receding expansion waves reach the upper shock after a finite time and start it moving rearward. This motion reduces the pressure jump across the shock wave by reducing its velocity relative to the oncoming flow, a "dynamic effect." This effect is in competition with a "displacement effect," or the tendency for a shock wave in a more rearward position on an airfoil to be stronger. In other words, competing effects determine the actual instantaneous shock strength, which is a function both of its change in position and of its velocity relative to the airfoil. The essential unsteady features of this problem, therefore, are the long and nonlinear transit time of the upstream-moving waves and the change in shock-wave strength due to its motion over the airfoil.

In practical cases, the unsteady shock-wave motion can lead to limit-cycle flutter oscillations of the control surface. This occurs when the phase of the
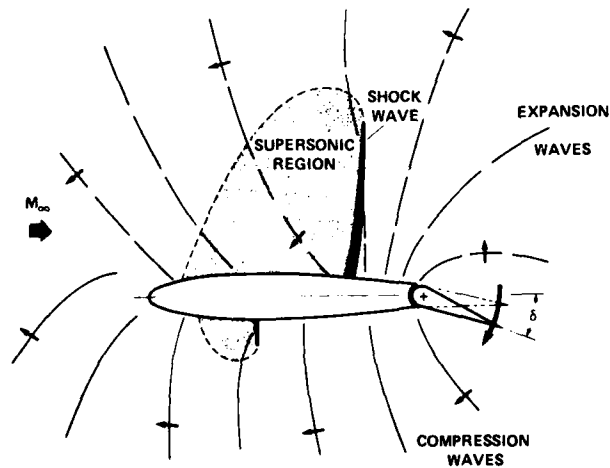

FIG. 6.—Transonic Flow Field on Airfoil with Oscillating Flap

unsteady pressure distribution relative to the flap motion permits the control surface to extract energy from the air stream. In addition, the interaction of the shock wave with the boundary layer introduces still other mechanisms for flutter instabilities. An example of the latter is shown by the intermediate Mach number case shown in Fig. 7 which is from Ref. 7. These results were obtained by elaborate numerical calculations, but the same behavior was observed experimentally. In Fig. 7, the airfoil is fixed and the free-stream flow is nominally steady. The flow at $M_\infty = 0.72$ is characterized by a weak shock wave and trailing edge separation, both of which fluctuate only slightly and irregularly. The flow at $M_\infty = 0.78$ fluctuates somewhat more, but it could still be classified as quasisteady in an overall sense. However, the case $M_\infty = 0.75$ is highly unsteady; it is characterized by distinctly periodic shock-wave motion and oscillations in boundary-layer separation between the trailing-edge and shock-in-

duced types sketched in Fig. 5. The reduced frequency of the oscillatory flow field was $k = 0.4$, and the amplitude of the fluctuating pressure coefficient was found to be of the same order as the average C_p on the airfoil. (In this and all subsequent figures, the reduced frequency has the definition that has evolved from potential-flow theory, $k = \omega c/2U_\infty$, in which c = the chord of the airfoil.)

In general, transonic flows that involve large amounts of boundary-layer separation are extremely difficult to analyze theoretically or to predict with any degree of confidence. Nevertheless, the calculations displayed in Fig. 7 show that time-dependent calculations of the Reynolds averaged, compressible Navier-Stokes equations can predict the phenomena in some detail. Even though such calculations are presently much too lengthy for routine engineering predictions, the study reported in Ref. 7 is extremely encouraging.
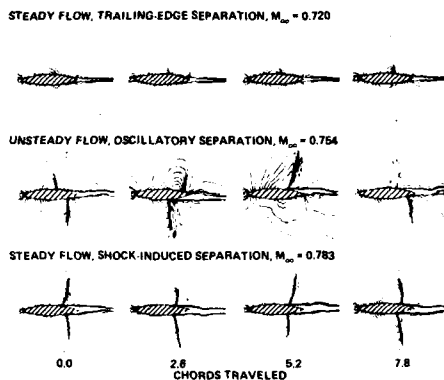

FIG. 7.—Calculated Mach Numbers Contours for Three Types of Shock-Wave Boundary-Layer Interaction on Stationary Circular-Arc Airfoil (R = 1.1 × 10⁷; Airfoil Thickness Ratio = 0.18)

Dynamic Stall and Stall Flutter.—A certain degree of unsteadiness always accompanies the flow over an airfoil or other streamlined lifting surface at high angle of attack, α, but the stall of a slender body undergoing unsteady motion is even more complex than static stall. If the angle of attack oscillates around the static stall angle, then large hysteresis develops in the fluid dynamic forces and moments. The maximum values of the lift, drag, and pitching moment coefficients, C_L, C_D, and C_M, can greatly exceed their static counterparts.

In addition, a condition of negative aerodynamic damping in pitch often develops during part of the cycle. This is shown by the dotted shading in Fig. 8 which is from Ref. 8. The aerodynamic pitch damping is given by $\zeta = -\oint C_M d\alpha$. If the average value of ζ over the cycle is negative, then the airfoil extracts energy from the air stream, and the pitch oscillations will tend to increase in amplitude, unless restrained. This, of course, is the condition for flutter, and unsteady separation hysteresis permits it to occur in a single degree of freedom of oscillatory body motion. Normally, in unseparated flows, flutter only occurs when the body motion includes multiple degrees of freedom, e.g.,

combined bending and torsion of an aircraft wing.

A great deal has been learned about the basic phenomena of dynamic stall within the last decade, especially in connection with the retreating-blade stall problem of helicopter rotors in forward flight. This problem is both three-dimensional and unsteady, since the velocity components arise from the combined rotational and translational motion of a rotor blade element. The component normal to the leading edge of the blade is given by $\Omega r + V_\infty \sin \Omega t$ and the spanwise component by $V_\infty \cos \Omega t$, in which the nomenclature is indicated

FIG. 8.—Force and Moment Coefficients on Oscillating Airfoil at Several Mean Angles (Pitch Axis at $x/c = 0.25$; $R = 4.8 \times 10^6$)

in Fig. 9. This produces a time-dependent yaw angle of the blade element

$$\Lambda = \tan^{-1}\left(\frac{V_\infty \cos \Omega t}{\Omega r + V_\infty \sin \Omega t}\right) \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (1)$$

and time-dependent blade incidence changes that vary with Ωt in a manner that is very approximately sinusoidally.

Fig. 9 shows the variations in chordwise velocity, angle of attack, normal force coefficient, and pitching-moment coefficient that were measured on a model helicopter rotor blade at two values of rotor thrust coefficient and reported in Ref. 11. Tested as a stationary wing, the rotor blades stalled at $\alpha \simeq 12°$,

for which $C_{L\,max} \simeq 1.0$, and the maximum negative value of C_M was about -0.15. Fig. 9 shows that considerably larger values of C_L and $-C_M$ were realized in the rotor test, and these large discrepancies between fixed-wing and rotor conditions are thought to be primarily due to the unsteady effects associated with the time-dependent variations in α.

Tests on two-dimensional oscillating airfoils have reproduced most, but not all, of the aerodynamic features shown in Fig. 9, as examined in Refs. 2, 12, 13, 18, and 23. On an airfoil with a rapidly increasing incidence, the onset of stall can be delayed to incidences considerably in excess of the static stall angle. If the airfoil attains a sufficiently high incidence by virtue of large-amplitude motion to penetrate deeply into stall, then the breakdown of the flow field begins with the formation of a strong vortex-like disturbance shed from the leading-edge region. This vortex moves downstream over the upper surface
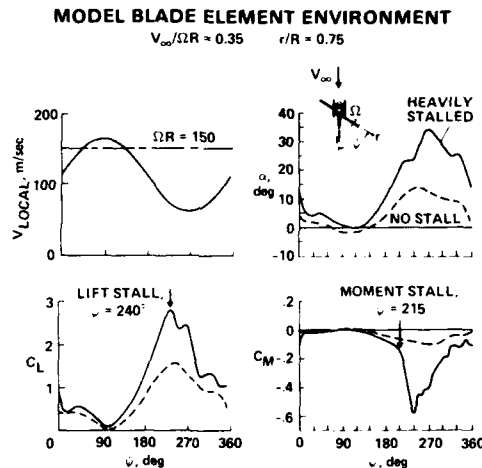
MODEL BLADE ELEMENT ENVIRONMENT

$V_{\infty}/\Omega R = 0.35 \qquad r/R = 0.75$

FIG. 9.—Aerodynamic Environment on Model Helicopter Rotor; Blade Radius [R = 4 ft (1.2-m)]

of the profile. Its passage distorts the chordwise pressure distribution and produces transient forces and moments that are fundamentally different from their static counterparts. These can not be reproduced by neglecting the unsteady motion of the airfoil. Another feature of the unsteady stall case is that the vortex shedding phenomenon distorts the pressure distribution and shifts the aerodynamic center of pressure rearward while the lift is still increasing. This produces large negative values of pitching moment, i.e., "moment stall," before the maximum in lift or normal force or "lift stall" occurs. Under quasisteady conditions, lift stall and moment stall occur approximately simultaneously.

The various parameters that influence dynamic stall have been summarized in Refs. 12, 18, and 23. It has been found that the details of dynamic stall depend strongly upon the frequency of oscillation, the amplitude of the motion, the mean angle of attack and, in some cases, upon the airfoil geometry. The

effect of the Mach number seems fairly important, although the extent to which the vortex shedding phenomenon is suppressed by shock-wave boundary-layer interaction has not been established. The general vortex shedding phenomenon has been observed and documented over wide ranges in Reynolds numbers in Refs. 3, 10, 11, and 29, but the detailed behavior of the aerodynamic force and moment coefficients seems to depend strongly upon this parameter only for $R \leqslant 10^6$.

The related phenomenon of stall flutter also involves oscillations in pitch, but as mentioned earlier, the amplitude of the oscillation is usually smaller than in the case of dynamic stall. When this is true, the large-scale, organized vortex-shedding phenomenon just described is absent or much less prominent. Nevertheless, the hysteresis in C_M versus α, which is necessary to produce the negative aerodynamic damping that initiates stall flutter, still has its origins in the phase of the nonlinear separation and reattachment of the boundary layer. Consequently, the frequency of the oscillation, which is approximately the torsional natural frequency of the structure, is a predominant parameter. The airfoil geometry and the free-stream Mach number largely determine the boundary-layer separation characteristics, and therefore they are also important.

INTERNAL FLOWS

Unsteady separated flows in ducts with variable geometry and in turbomachinery, exhibit many features in common with the aforementioned external flows.
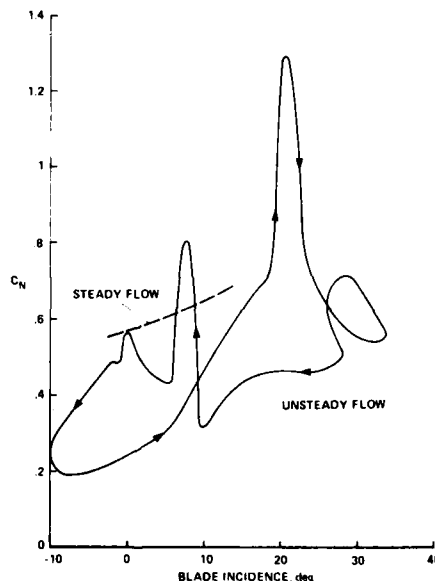

FIG. 10.—Normal Force Coefficient for Dynamic Stall on Compressor Rotor Blade Due to Inlet Distortions

However, there are important differences which are described briefly in the following representative examples.

Axial-Flow Compressors.—The qualitative features of dynamic stall and stall flutter have been observed in compressors and their nonrotating analogs, cascades. However, the interference between adjacent blades and three-dimensional and rotational effects have a strong influence on the quantitative details of the stall behavior, as examined in Refs. 13, 14, 19, and 24. In particular, the hysteresis loops of forces and moments are considerably more complicated than those of isolated airfoils, as indicated in Fig. 10, which is from Ref. 17. Furthermore, in this experiment the maximum normal force was observed to increase approximately linearly with the nondimensional pitch rate, but the rate of increase of C_N in this correlation was much less than in the isolated airfoil case. More detailed measurements will be required to determine to what extent stall on rotating components can be understood in terms of the semi-empirical analyses and concepts of dynamic stall on airfoils, wings, and helicopter blades.

The global unsteady stall problems of surge and rotating stall in turbomachines may be mentioned in passing. As their names suggest, rotating stall is a large-scale

ROTATING STALL   SURGE

CIRCUMFERENTIALLY   AXIALLY OSCILLATING
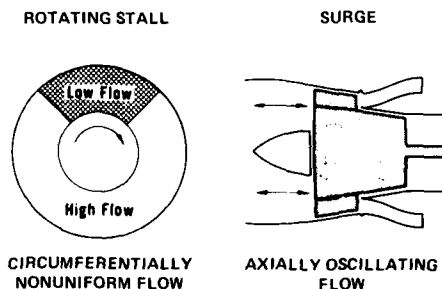NONUNIFORM FLOW   FLOW

FIG. 11.—Sketch of Two Possible Modes of Compressor Instability

separation phenomenon that normally propagates circumferentially in a direction opposite to the rotor motion, whereas surge induces mass flow oscillations in the axial direction. These two modes are indicated schematically in Fig. 11, which is from Ref. 14. Because of their complexity and interdependence upon the total system parameters, few analyses or experimental investigations have focused upon the detailed fluid dynamic behavior inside such machines.

Transitory Stall in Diffusers.—A different type of stall occurs in diffusers operating close to their maximum pressure recovery. As indicated in Fig. 12, basic flow regimes for low speed flows were identified some years ago by Fox and Kline (5). Some of the transonic modes that were classified more recently in Ref. 20 are sketched in Fig. 13. In these transitory stall regimes, large amplitude fluctuations can occur more or less periodically as the separated fluid washes in and out of the downstream end of the diffuser, or as the stalled region grows and collapses in the lateral direction. As shown in Fig. 13, the unsteadiness in the supercritical modes is caused by the unsteady shock-wave boundary-layer interactions.

The frequency of the transitory stall in low-speed two-dimensional configura-

tions has been found in Ref. 25 to be given very approximately by $(f\ L\ \sin \theta)/U_o = 0.0055$, in which L = the length; U_o = the average entrance velocity;

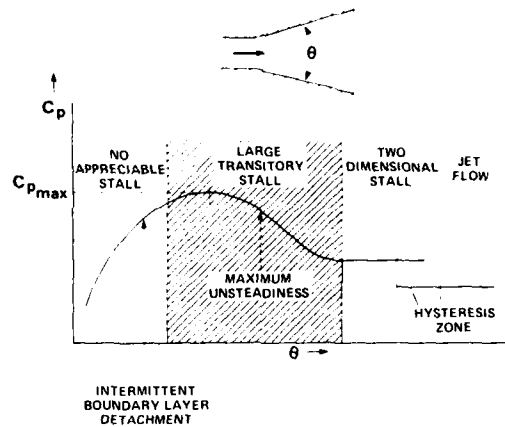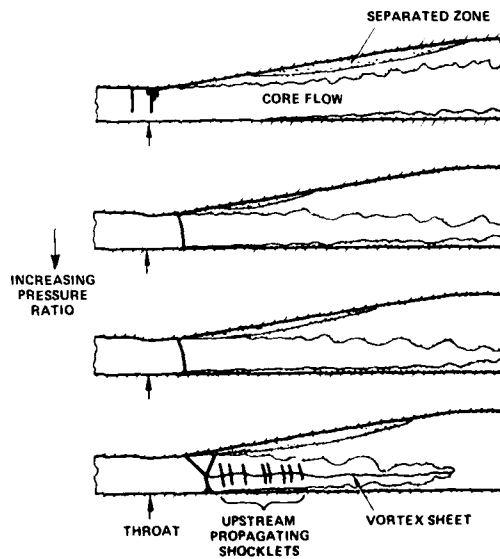FIG. 12.—Flow Regimes in Two-Dimensional Low-Speed Diffusers

FIG. 13.—Typical Instantaneous Flow Patterns in Transonic and Supersonic Diffusers

and θ = the total included angle of the diffuser. For the maximum amplitudes of the fluctuations, typical values of θ are in the range $15°-30°$, which would mean $\omega L/U_o \simeq 0.1$. It has not yet been established whether this represents

a truly unsteady problem, insofar as the overall performance is concerned. However, for the large-amplitude oscillating airfoils, this range of reduced frequencies represents a regime wherein unsteady effects grow rapidly with increasing frequency.

CONCLUDING REMARKS

Almost any flow that separates will have some degree of unsteadiness. In some cases, the fluctuations will be almost completely stochastic, in others, highly organized, and in still others, there will be a combination of random and periodic components. In this paper some of the peculiar unsteady phenomena have been reviewed and several broad classes of flow problems have been analyzed briefly. It should be emphasized again that a great deal remains to be learned about unsteady separated flows, especially at high Reynolds numbers. Whether external or internal, fundamental understanding and satisfactory engineering prediction methods for flows of this type are lacking. However, all are presently receiving considerable attention, and improvements are developing rapidly. The ability to predict and suppress unsteady separation should lead to substantial improvements in the performance, reliability, and costs of a wide range of fluid dynamic devices.

APPENDIX.—REFERENCES

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16327 CHALLENGE OF UNSTEADY SEPARATING FLOWS

KEY WORDS: **Aerodynamics;** Aerodynamic stability; Aeroelasticity; **Airfoils;** Boundary layer separation; Buffeting; Flow characteristics; **Flow separation; Fluid dynamics; Fluid flow;** Flutter; Oscillation; Shock waves; Unsteady flow; Vortices

ABSTRACT: Unsteady effects produce strong or unusual changes in the flow separation characteristics of many modern fluid dynamic devices. The peculiar physical phenomena are described that are involved in unsteady flows past cylinders, airfoils, wings, and rotating blades and in unsteady flows within turbomachines and diffusers. The recent fundamental research on these topics is reviewed briefly. The combination of unsteadiness and flow separation manifests itself in vortex shedding, buffet, dynamic stall, stall flutter, shock-wave boundary-layer interaction, compressor stall, and transitory stall in diffusers. These complicated fluid dynamic processes, which are extremely difficult to predict, often produce undesirable fluctuating forces, vibrations, and aeroelastic instabilities. Much additional research and engineering efforts are needed to develop the tools for predicting and controlling the effects of unsteady flow separation.